Using EEG to Detect and Monitor Mental Fatigue

L. D. Montgomery, R.W. Montgomery
Lockheed-Martin

B. Luna, L. J. Trejo

NASA Ames Research Center, Moffett Field, CA 94035

ABSTRACT OR SUPPORTING INFORMATION

Presentation to be given at Human.Systems 2001: The Conference on Technologies for Human Factors and Psycho-Social Adaptation, NASA Johnson Space Center, June 20-22, 2001.

Title: USING EEG TO DETECT AND MONITOR MENTAL FATIGUE

Leslie Montgomery, Bernadette Luna, Richard Mongtomery, Leonard J. Trejo

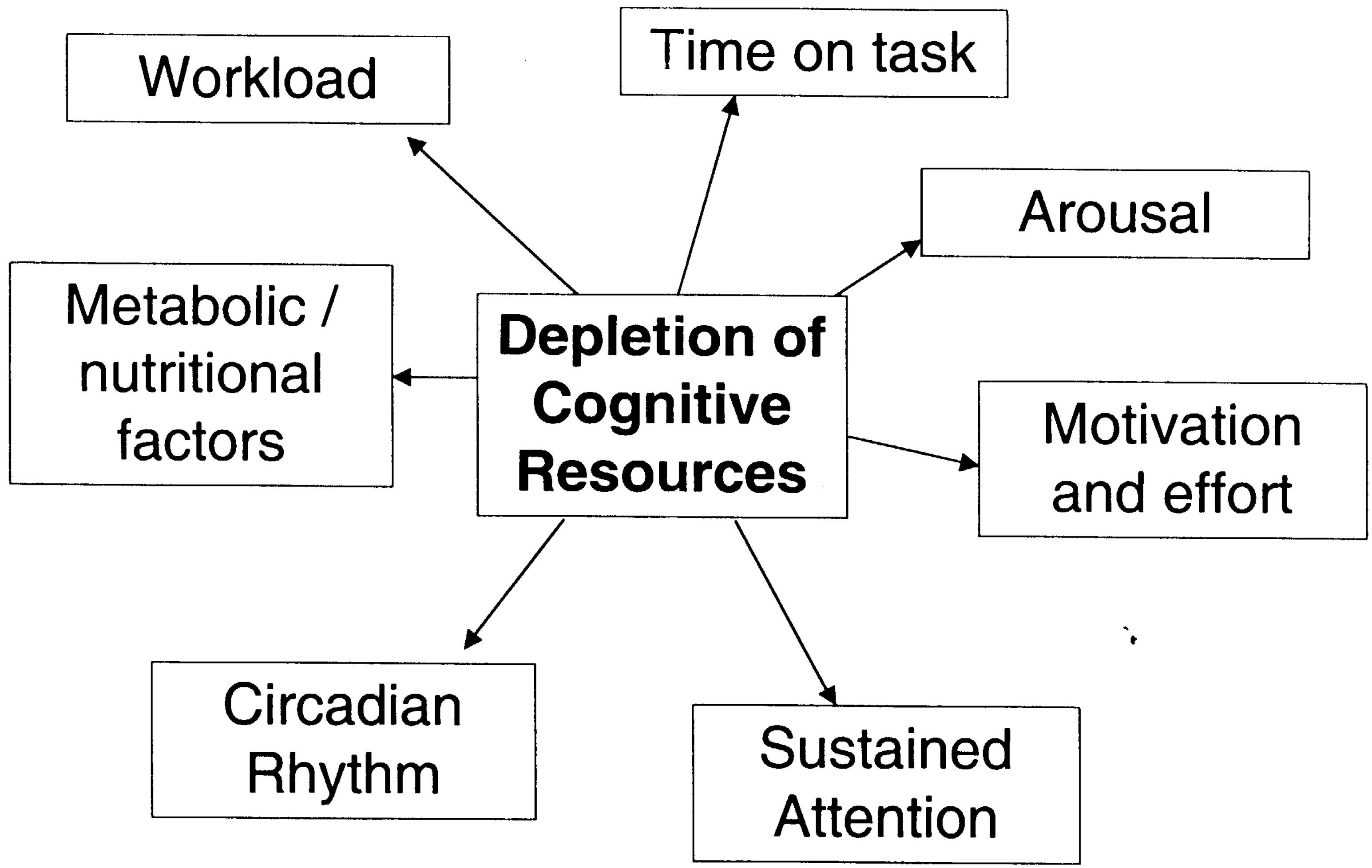
Abstract (poster presentation)

This project aims to develop EEG-based methods for detecting and monitoring mental fatigue. Mental fatigue poses a serious risk, even when performance is not apparently degraded. When such fatigue is associated with sustained performance of a single type of cognitive task it may be related to the metabolic energy required for sustained activation of cortical areas specialized for that task. The objective of this study was to adapt EEG to monitor cortical energy over a long period of performance of a cognitive task. Multielectrode event related potentials (ERPs) were collected every 15 minutes in nine subjects who performed a mental arithmetic task (algebraic sum of four randomly generated negative or positive digits). A new problem was presented on a computer screen 0.5 seconds after each response; some subjects endured for as long as three hours. ERPs were transformed to a quantitative measure of scalp electrical field energy. The average energy level at electrode P3 (near the left angular gyrus), 100-300 msec latency, was compared over the series of ERPs. For most subjects, scalp energy density at P3 gradually fell over the period of task performance and dramatically increased just before the subject was unable to continue the task. This neural response can be simulated for individual subjects using a differential equation model in which it is assumed that the mental arithmetic task requires a commitment of metabolic energy that would otherwise be used for brain activities that are temporarily neglected. Their cumulative neglect eventually requires a reallocation of energy away from the mental arithmetic task.

Some Health Hazards in Long-Duration Missions

- Cephalad Fluid Shifts/Loss
  - Orthostatic intolerance upon reentry
  - Venous thrombosis
- Bone Demineralization
  - Fractures
  - Kidney stones
- Muscle Atrophy
  - Loss of strength
- Cardiovascular Deconditioning
  - Heart problems
  - Hypertension
- **Isolation/Confinement/Stress**
  - **Neurobehavioral dysfunction**
- Repetitive Motion Syndrome

Cognitive Fatigue



Previous Research

Multiple Sclerosis

- Evidence of EEG energy density correlations (Montgomery et al.)
- Krupp & Elkins (2000) - declines in single session

Lyme Disease

- Pollina et al. (1999) - cognitve deficits in speeded tasks, not seen in controls or depressed patients

Extended Wakefulness: ERP & Performance Studies

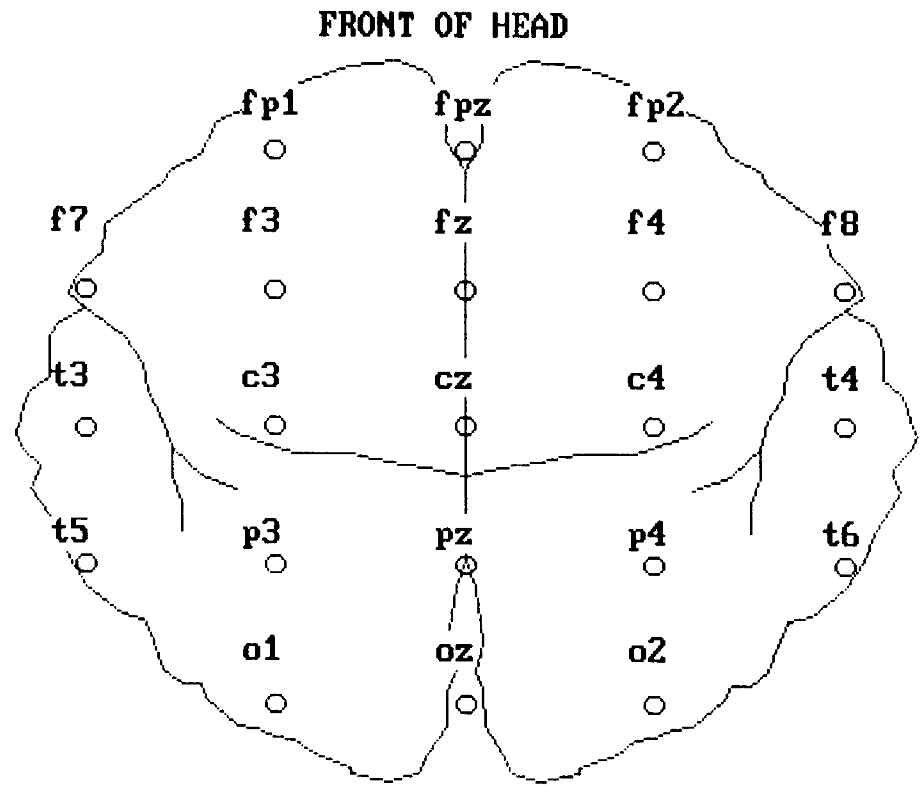
- Declines in early perceptual processes -- Humphrey, Kramer & Stanny (1994)
- Decreased effectiveness of error detection processes (Scheffers et al. 1999)

Mental Arithmetic Task

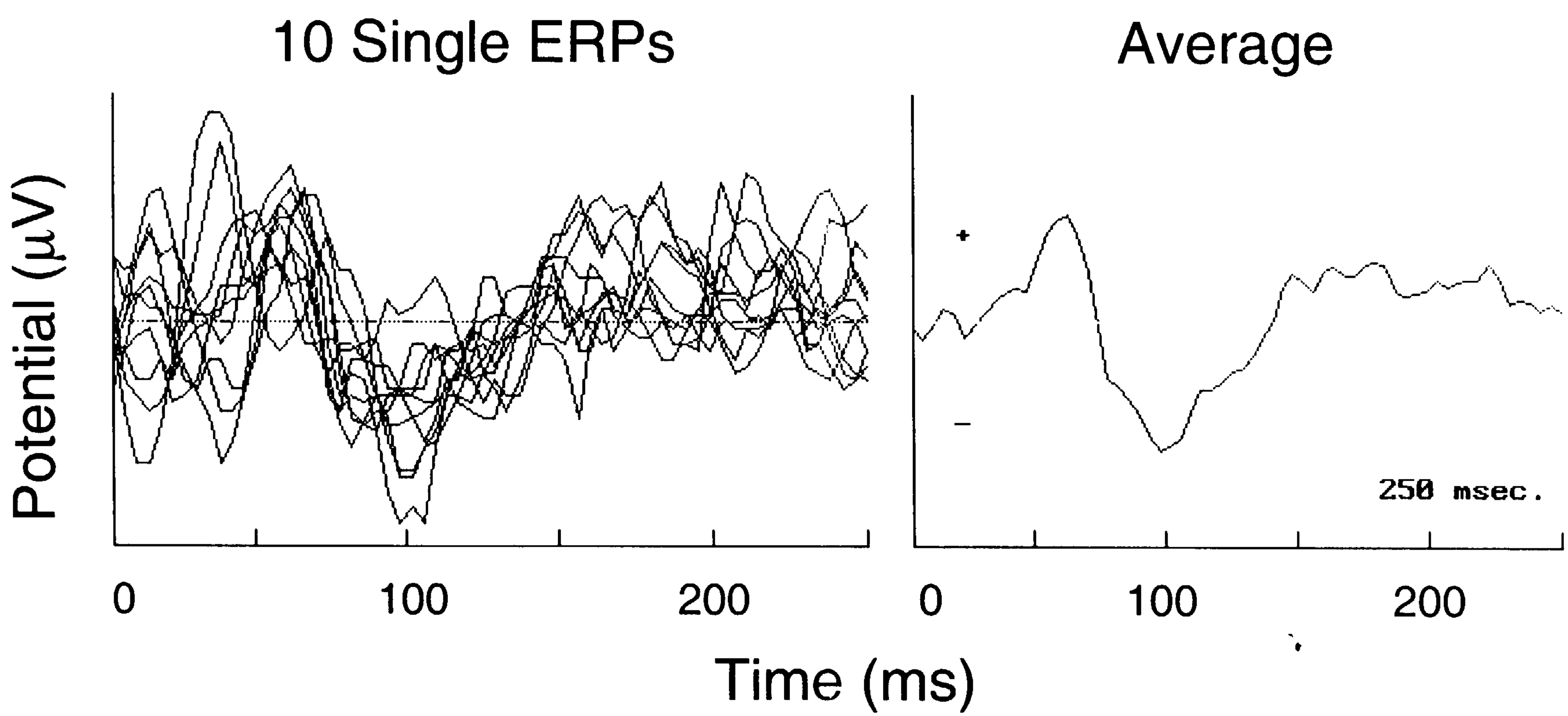
+ 1 - 5 + 6 + 9

< = > 11?

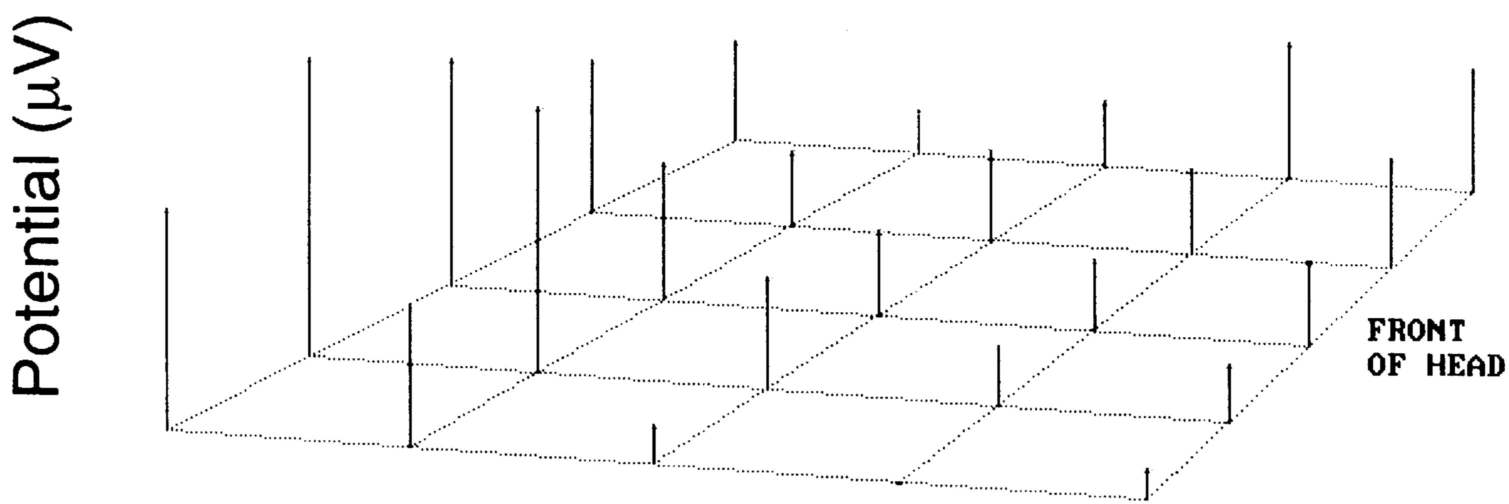
Electrode Locations



Sample Single and Averaged ERPs



Sample EEG Surface Potential Distribution



2-D Projection of Electrode Location

Surface-Fitting Equation for Potentials

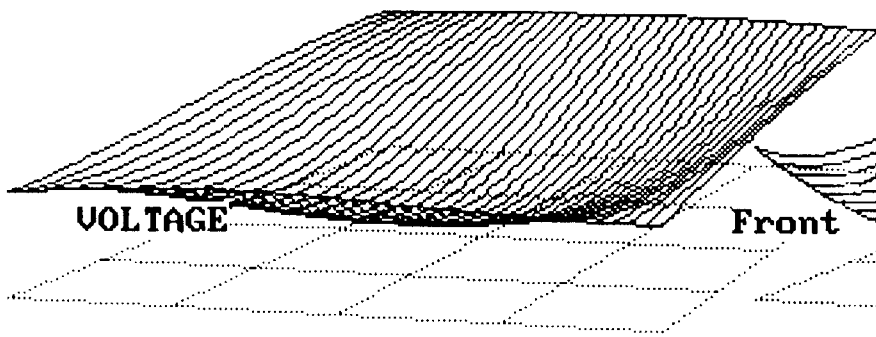
V = potential at electrode coordinates X, Y
X = side-to-side direction in 2-D projection
Y = front-to-back direction in 2-D projection

$$V = (a + bX + cY + dXY)^3$$

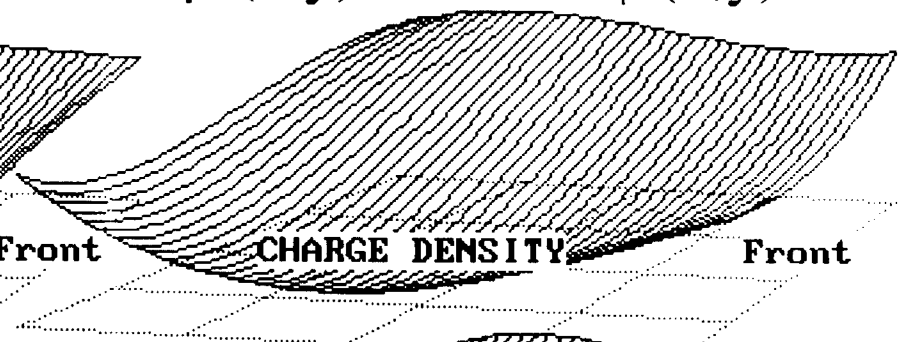
$$V = (b_1 + b_2X + b_3X^2 + \ldots\ldots + b_{15}X^2Y^3 + b_{16}X^3Y^3)$$

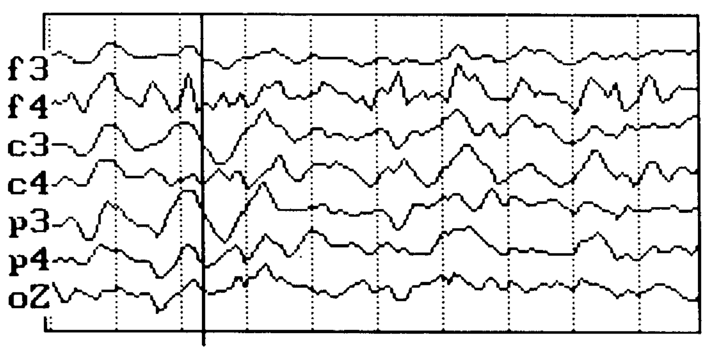
Derivation of EEG Energy Density Surface

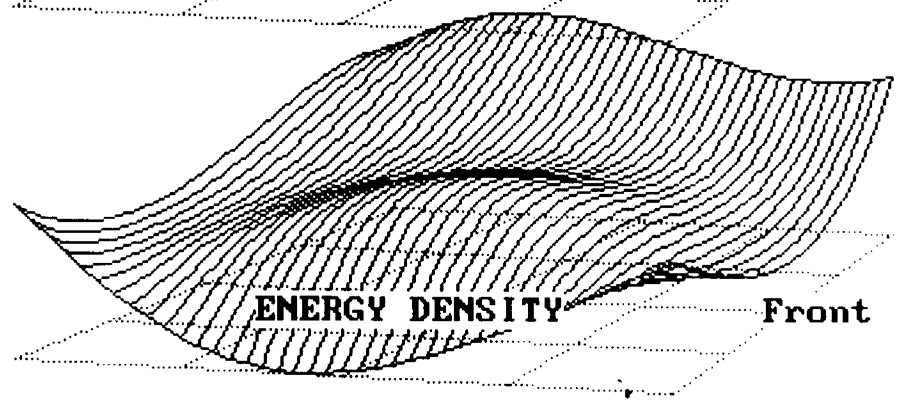
$\phi(x,y)$



$\rho(x,y) = -\varepsilon \nabla^2 \phi(x,y)$

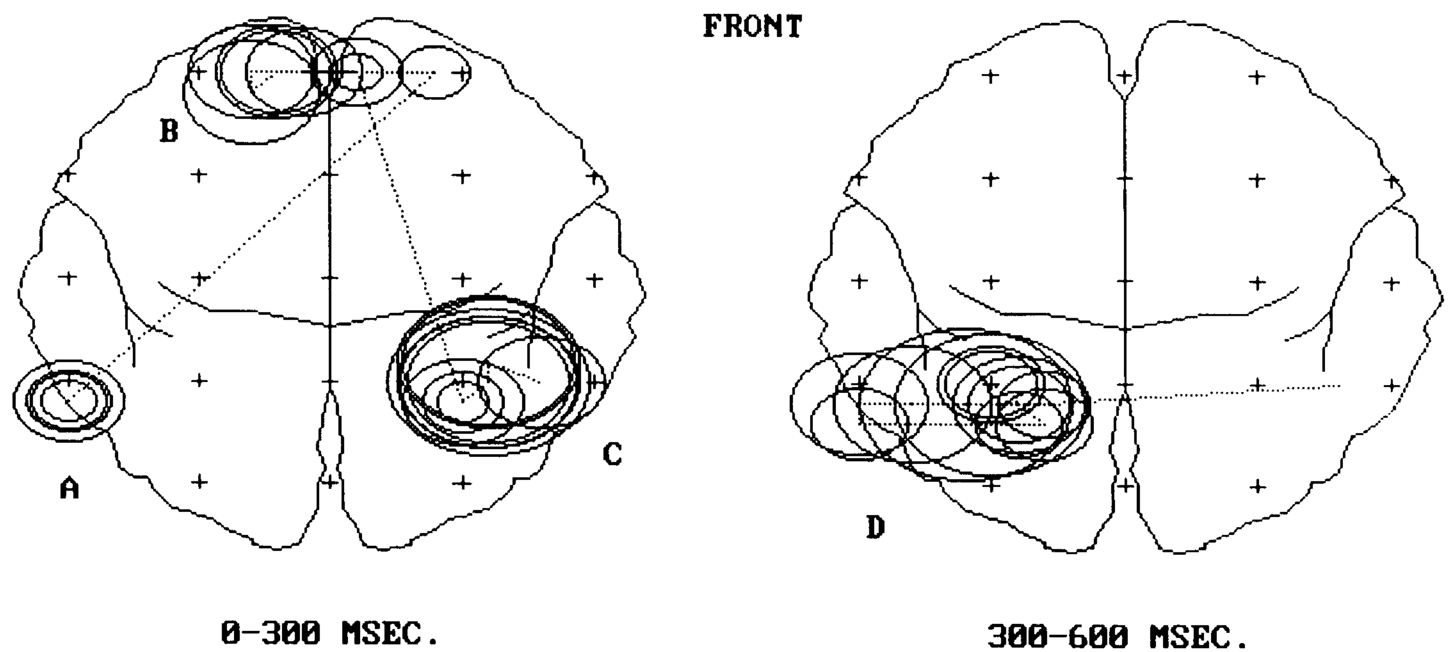






$U = -\varepsilon \phi \nabla^2 \phi.$

Average Maxima of Measured Energy Density

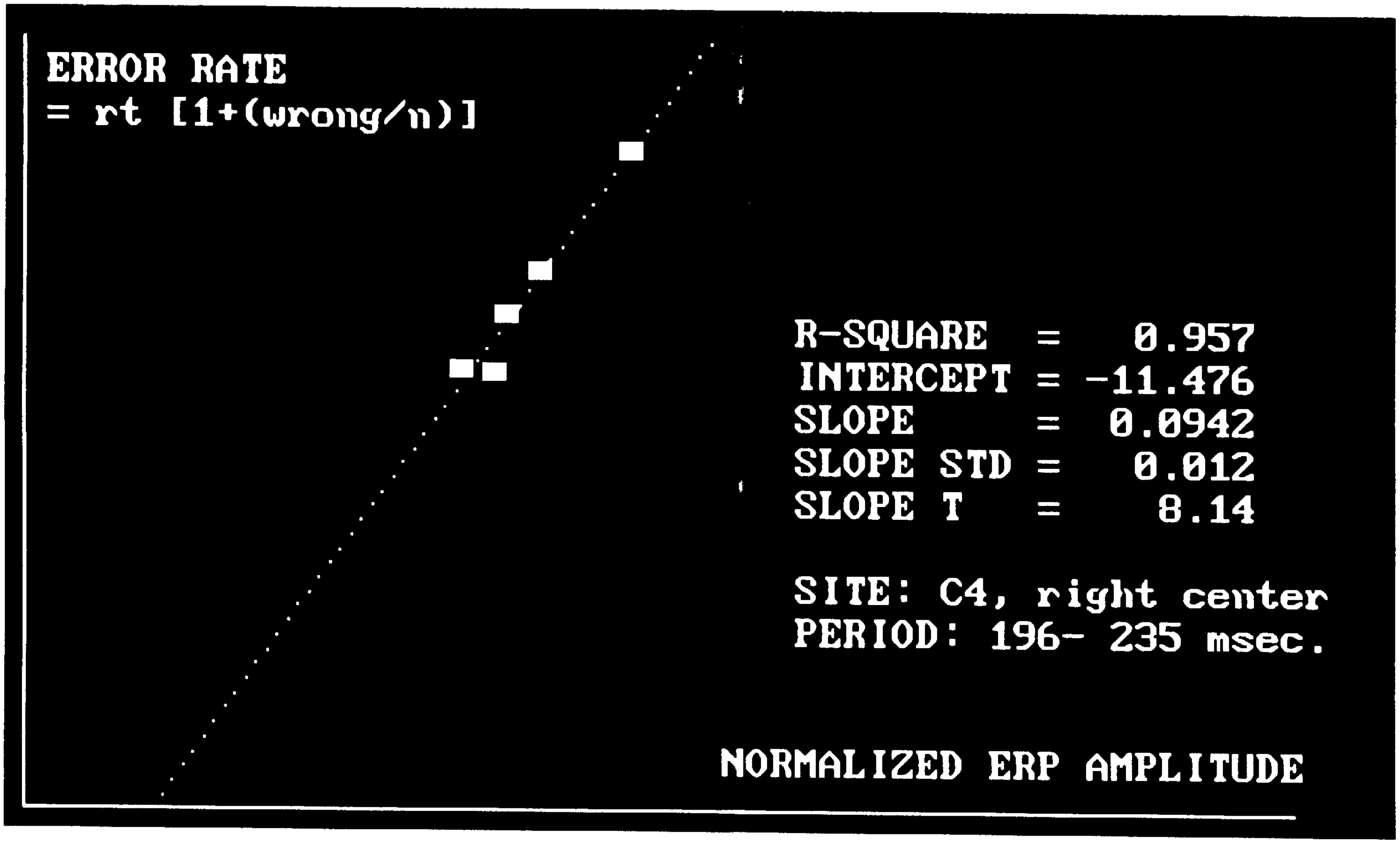


Task Error Index vs. Energy Density

Index = RT × (1 + wrong / n)

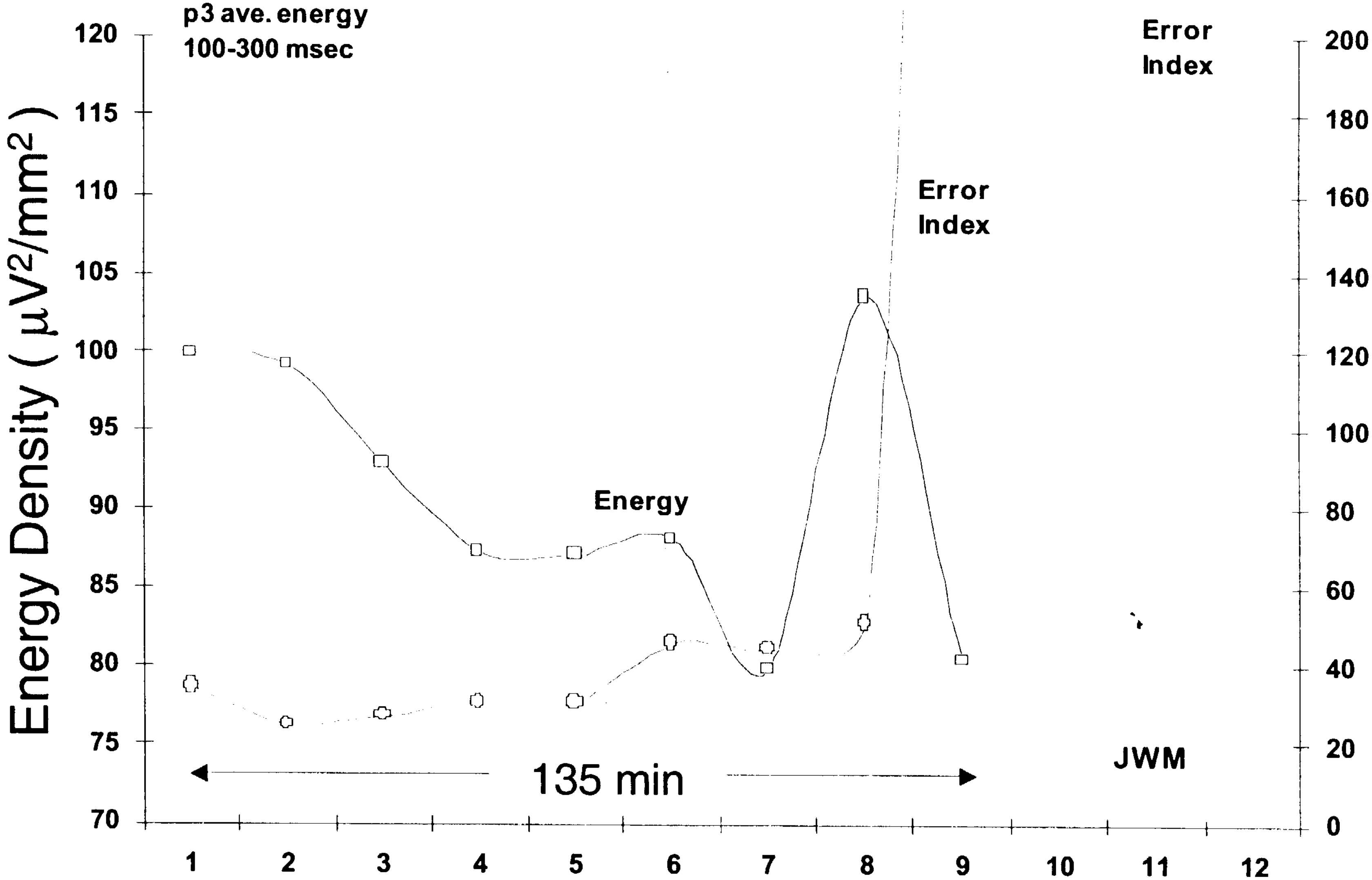
Electrode	Period (ms)	r^2	Slope T
T5	47-86	0.913	-5.624
T5	55-94	0.948	-7.402
FPZ	86-126	0.877	-4.624
FPZ	94-133	0.897	-5.122
F3	102-141	0.878	-4.639
FPZ	110-149	0.856	-4.609
FPZ	118-157	0.876	-4.223
P4	141-180	0.851	4.134
P4	149-188	0.878	4.657
P4	157-196	0.882	4.740
P4	165-204	0.869	4.458
T5	172-211	0.914	-5.637

Group Performance vs. Energy Density



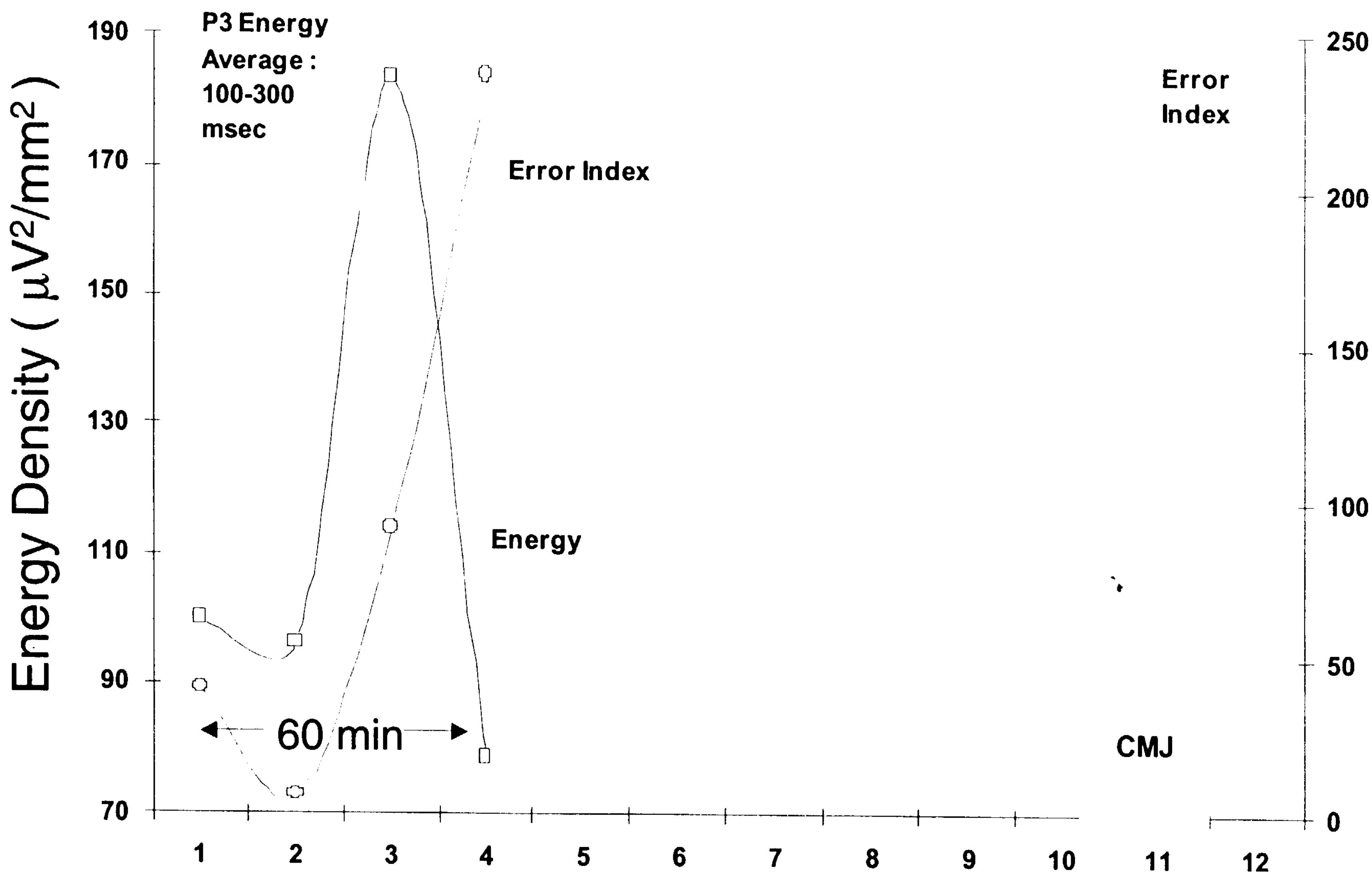
Performance & Energy Density Over Time

Normal Subject



Performance & Energy Density Over Time

Subject Who Reported Feeling Sick



Future Plans

Improve Spatial and Computational Resolution

- 64 electrodes (128 electrodes in some subjects)
- Spline Laplacian (Nunez)
- Separate estimates of radial (gyral) and tangential (sulcal) current source densities
- Comparison of Montgomery's energy density with CSD and potential measures

Addition of irrelevant auditory probe

- Low level aperiodic random tone series
- Individual calibration
- Analysis of performance-related ERP component changes

Irrelevant Probe ERPs and Mental Effort

Electronic Warfare Simulation

(Kramer, Trejo & Humphrey, 1996)

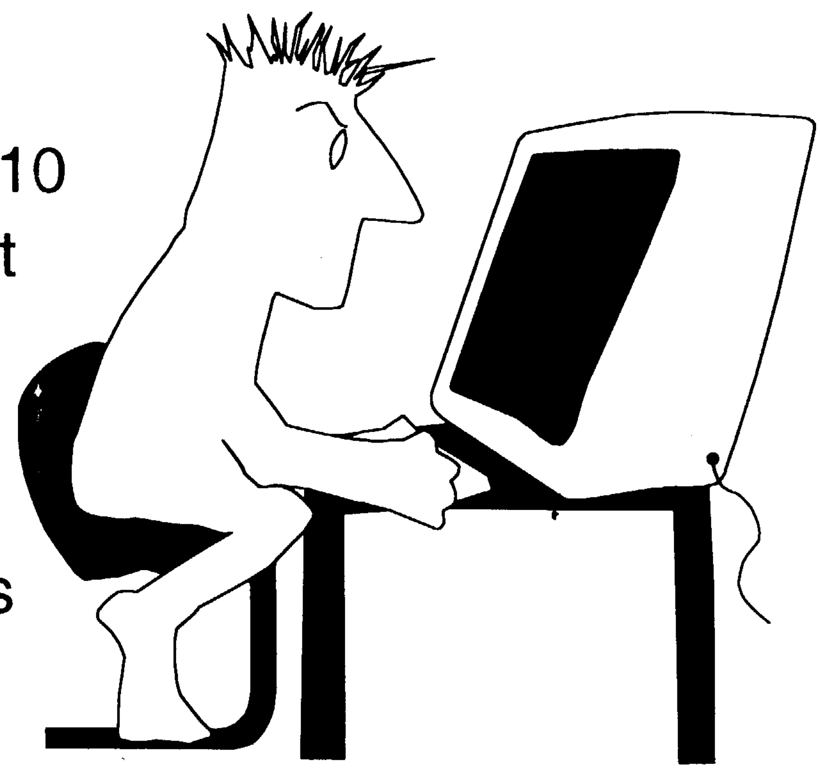
10 experienced EWs

Baseline task

- Auditory oddball 80/10/10
- Respond to one deviant tone

1-hr mission scenario

- Realistic Simulation
- Auditory oddball probes
- Variable target density over time



ERP Results with Probe Stimuli

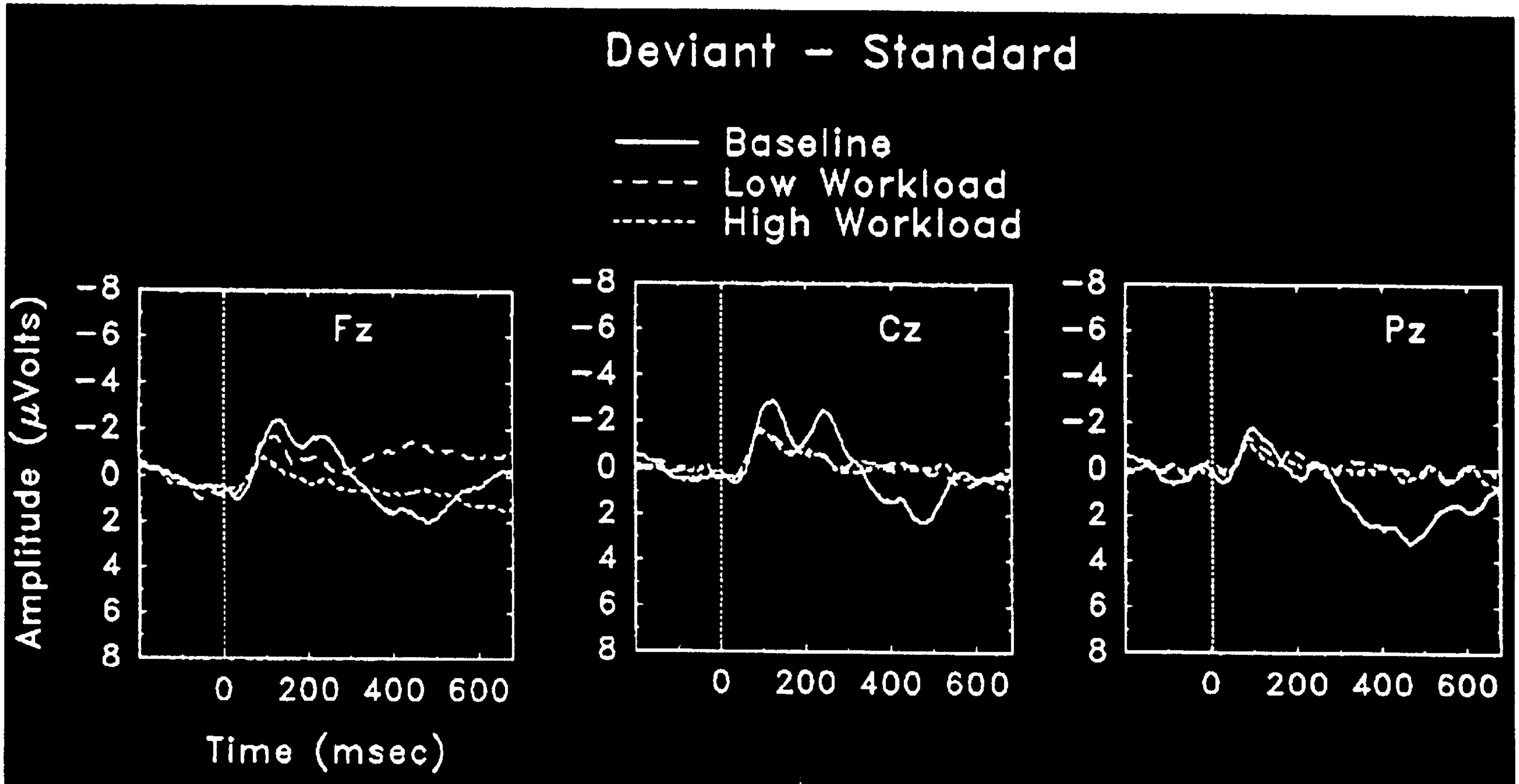


FIG. 7.5. Grand average waveforms derived by subtracting the ERPs elicited by the standard tones (e.g. the tones which occurred on 80% of the tone trials) from the ERPs elicited by the deviant tones.

Summary of Results with Probe Stimuli

Baseline task

Deviant tones

- Large N1, N2
- P3 elicited only by target deviants

Deviant vs. standard

- Mismatch negativity for both deviants

EW Simulation

Standard tones

- Reduced N1, N2

Deviant tones

- No P300
- Reduced N1, N2
- Reduced MMN

Both tone types

- Reductions covary with scenario complexity

Conclusions and Recommendations

Energy Density

- Initial data show potential onset of cognitive fatigue
- Confirm results with high-resolution source imaging and modeling, and ERP component analysis

Probe ERPs

- Prior data show tracking of mental workload
- Extend application to monitoring of cognitice fatigue
- Combine probes with mental math task and source imaging

Using EEG to Detect and Monitor Mental Fatigue

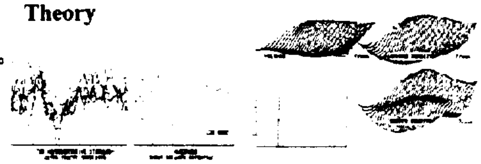
L. D. Montgomery, R.W. Montgomery, Lockheed-Martin; B. Luna, L. J. Trejo, NASA Ames Research Center, Moffett Field, CA 94035

Motivation

[illegible] several [illegible] a long and static work cycle. Multi-tasking, intense work load, a sub-optimal display, stress, fatigue, and distraction — any one of these can eventually lead to performance errors.

It would be desirable to predict deterioration in an individual's performance of demanding [illegible] significant performance deterioration is predicted — even if the pilot is able, through extra effort, to maintain an adequate level of performance for a time.

Theory

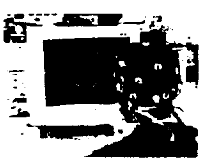


[illegible] relate potentials measured on the scalp to underlying physiological processes. Efforts have focused on changes in [illegible] waveform transformation. Energy density as defined here may provide the connection between scalp potentials and physiological effort.

An event related potential (ERP) is the averaged scalp voltage potential at a particular scalp location that is generated in response to a [illegible] With multielectrode ERP data, we can generate a voltage "map" at each sample time. From the [illegible]

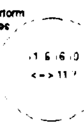
$$[illegible]$$

Experimental Methods & Results

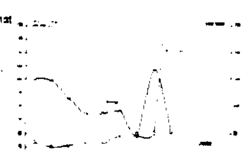


[illegible] time. Are the units of energy more meaningful than voltage? Can energy be related to performance during long duration tasks? During our first year, we refined our experimental procedures to permit us to measure performance and energy density over extended task durations.

Subjects are given an exhausting series of arithmetic problems to perform (see photo to left). They must respond using a keypad. Scalp voltages from 80 to 100 problems — about 8-14 minutes of elapsed time — [illegible] ERP. We collected one ERP every 15 minutes. We continued to take data until the subject stated they could no longer continue. Our most dedicated subject performed about 3600 problems over a period of 3.5 hours. We are looking for changes in performance over the test period, and for changes in energy density ERPs over the same time period.

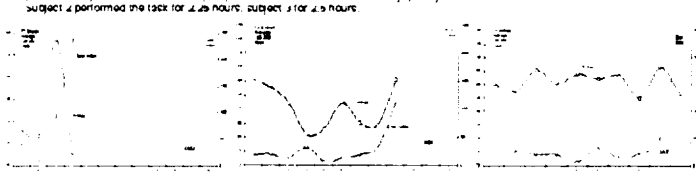


The figure at right illustrates the typical performance and neural activity response that we observed. We found a response that was consistent across most subjects.



The blue line represents the subject's error index. All subjects' performance deteriorated dramatically during the final ERP (just before they refused to continue), [illegible] time. Thus, we found performance to be a very poor predictor of exhaustion.

The red line represents energy density at p3 (near the left angular gyrus, the mathematical processing center in the left hemisphere). Energy density generally decreased with time, and exhibited a peak and sharp decline just prior to the exhaustion. This behavior is apparent in subjects who tested for different time periods. Subject 1, below, was sleep-deprived and reached exhaustion very quickly; subject 2 performed the task for 2.25 hours, subject 3 for 2.5 hours.



The evolution of the EEG pattern during the task time can be explained in terms of the rising cost of "borrowing" metabolic energy resources from other "maintenance type" or homeostasis brain activities in order to sustain concentration on the mental arithmetic task at hand. If the cost of neglect of these maintenance activities is cumulative, it is logical to expect the brain to eventually reduce [illegible]

A simple mathematical model can be used to illustrate such a resource allocation process as illustrated below.

PROPOSED MODEL

M (resource allocation rate to mental arithmetic) is a diversion of resources otherwise fully available as H (allocation rate to homeostasis):

$$M = 1 - H$$

Homeostasis neglect (NH) [illegible]

$$NH = \int (HH - H)\, e^{t}\, dt$$

Mental arithmetic neglect (NM) is simply the shortfall relative to required rate:

$$NM = RM - M$$

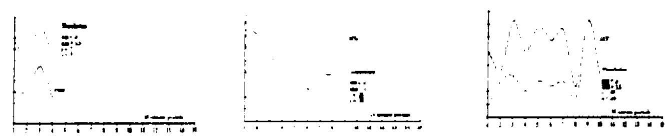
The homeostasis resource flow is regulated to balance the neglected functions:

$$dH/dt = a\,(NH - NM)$$

These equations simplify the system to one overall 2nd order differential equation, which in operator notation becomes:

$$(D^2 + a\,D + a\,e^{t})\,H = a\,RH$$

With parameter (r, a, RM, RH) fitting, this model was used to simulate the experimental electroencephalographic data of the three subjects shown earlier. As shown below, we were able to [illegible] for each subject. Please note that these figures illustrate that the model can be used to successfully reproduce the relative shape of each subject's response. The two traces in each figure are intentionally separated to provide a better comparison of the actual and simulated activity.



Summary

This study demonstrates that the energy density analysis of [illegible] EEG may be used to investigate the neural responses of human subjects [illegible] A quantitative EEG index was derived which may provide insight into the association between a subject's performance of a task and the [illegible] effort expended in the performance of the task. A resource allocation model was developed that can be used to explain the cognitive processing that may take place during long term task performance.

This work was supported, in part, by NASA Ames Research Center Director's Discretionary Fund and the Psychological and Physiological Stressors and Factors (PPSF) Project as part of NASA's Aerospace Operations Systems Program.

For additional information please contact Leslie D. Montgomery Tel: 650-604-0414, E-Mail: lmontgomery@mail.arc.nasa.gov

Suggested Reading

R. W. Montgomery, L.D. Montgomery, and R. Guisado. "Cortical localization of cognitive function by regression of performance on event related potentials." Aviat. Space Environ. Med. 63: 910-924, 1992.

R.W. Montgomery, L.D. Montgomery, and R. Guisado. "Electroencephalographic scalp energy analysis as a tool for investigation of cognitive performance." Journal of Biomedical Instrumentation and Technology 27(2): 137-142 (1993).

L.D. Montgomery, R.W. Montgomery, and R. Guisado. "Continuous monitoring of cerebral blood flow: Correlation of rheoencephalographic activity during cognition." Journal of Clinical Engineering 18(3): 235-244 (1993).

L. D. Montgomery and R. Guisado. "Rheoencephalographic and electroencephalographic measures of cognitive workload: Analytical procedures." Biological Psychology, 40: 143-159 (1995).